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A SURVEY OF BLASTING ACTIVITY IN THE UNITED STATES

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In many parts of the world, there are many more seismograms from chemical explosions (blasting) than from naturally occurring earthquakes; therefore, statistical information on chemical explosions is needed in the context of assessing seismic capability to monitor underground nuclear explosions. We have obtained data on blasting activity from three different sources: (1) overview information from the U.S. Bureau of Mines (USBM) on the total amount of chemical explosives used in the U. S. during 1987, with breakdowns into different explosive types, and

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usage by different states; (2) overview information from the Mine Safety and Health Administration (MSHA) on the numbers of mines, of different types, in the U. S.: and (3) detailed information from a private company (Vibra-Tech Engineers, Inc.) on total shot size and size of charge per delay for 20,813 blasts carried out in 1987 at 532 locations.

Our procedure has been to extrapolate the detailed information contained in the 1987 Vibra-Tech data for a limited number of states, and thus to obtain estimates for the whole country on numbers of shots and their size distribution. The extrapolation is constrained by the data from USBM (numbers of shots, sizes) and the MSHA (locations). Blasting activity does not fluctuate greatly from year to year and 1987 was representative of current practice.

Our main findings are that about 2.2 million metric tons of chemical explosive are used annually in the continental U. S., principally in mining for coal and metal ores. On a typical work day, there are roughly thirty explosions greater than 50 tons, including about one greater than 200 tons. There was one industrial explosion in 1987 at about 1,400 tons. For shots between one ton and one hundred tons, the cumulative distribution has a "b-value" near unity — that is, if N is the number of shots (per year) greater than or equal to W tons,

$$N \propto 10^{-b \log W}$$

with b roughly equal to 1. This result is similar to the size distribution of earthquakes greater than magnitude m_b,

$$N \propto 10^{-b\, m_b}.$$

Almost all chemical explosions above one ton are "ripple-fired." The typical shot uses 20 to 50 separate delays.

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A SURVEY OF BLASTING ACTIVITY IN THE UNITED STATES

BY PAUL G. RICHARDS, DOUGLAS A. ANDERSON, AND DAVID W. SIMPSON

INTRODUCTION

A general reason for seismologists to be interested in blasting activity is that, in many parts of the world, there are far more seismograms obtained from chemical explosions than there are from naturally occurring earthquakes. For purposes of studying Earth structure, explosion seismograms can be even more useful than earthquake seismograms, not only because of the better areal coverage, but also because it is often possible to get precise information on the source location and source origin time.

A specialized but very important reason to study blasting is in the context of discriminating nuclear explosions from other seismic sources. If the source was obviously large, so that if it were an explosion it would have to be greater than one kiloton, then it is usually possible to identify the source quite easily from analysis of seismic signals. See, for example, Taylor *et al.* (1989) and Richards and Zavales (1990). For smaller events the discrimination problem gets harder, because there are fewer signals with adequate signal to noise ratio, and also because the rate of occurrence increases. The statistics of this increase have been documented extensively for earthquakes, but the statistics for chemical explosions have not been available and were a goal of the present study.

The importance of chemical explosions in determining U. S. capability to discriminate nuclear explosions in the U. S. S. R. was summarized by the Office of Technology Assessment (U. S. Congress, 1988) as follows:

> ". . . there appears to be agreement that, with internal stations that detect down to m_b 2.0 - 2.5, identification can be accomplished in the U. S. S. R. down to *at least* as low as m_b 3.5. This cautious assessment is currently set by the uncertainty associated with identifying routine chemical explosions that occur below this level. . ."

The conclusion here is that chemical explosions are the limiting factor in setting the identification level for underground nuclear explosions.

The blasting agent most often used for industrial explosions is known as ANFO (an acronym for ammonium nitrate and fuel oil). ANFO delivers about 90% of the energy per unit mass obtainable with TNT, for which the term "kiloton" was originally defined. The modern definition of a kiloton, as an energy measure of nuclear explosion yield, is 10^{12}

calories. Where it is necessary in this paper to convert between pounds (lbs) and tons, we shall use the metric ton (containing about 2,200 lbs).

When we started in the mid-1980's to make informal inquiries about the extent of chemical explosion activity in the U. S., we were given much anecdotal information on shot sizes and explosion practice. Many mines and quarries will report blast times, but are often reluctant to release detailed information on explosion sizes because this may become the basis for damage claims. More forthcoming were suppliers of chemical explosive, and from them we soon learned of fourteen mines in the western and mid-western U.S. that routinely use ANFO for ripple-fired explosions in the range 100-500 tons. Table 1 lists the number of large blasts per year, and their sizes, at these fourteen mines.

TABLE 1

# of large blasts per year	Size of large blasts (tons of ANFO)
50	50–100
40	40–80
50	100 (one at 600)
20	200
80	100
25 & 150	100 & 60, respectively
100	100
50	400
25	500
20	350
30	200
50	150 and above
15	200
15	200

Numbers and sizes of large chemical explosions in fourteen U. S. western and mid-western mines.

There are many more mining explosions above 40 tons, and blasting above 10 tons occurs "all the time" in the west and mid-west. At times of lessened economic interest in mining these numbers of explosions are somewhat reduced, but individual mines are geared up to work with explosions of a certain size so the sizes do not change greatly. Because the shots are ripple-fired, the observed seismic signals are more complex and are significantly reduced in amplitude below what would be observed if the total charge were set off at the same instant in one location. Scientific papers on the resulting seismic signals have been published by Greenhalgh, Mooney and Mosher (1980) and Greenhalgh (1980), who report on blasts consisting of tens of rows each with ten or more holes, each hole filled with less than 1 ton of ANFO. A typical pattern in their studies was 20 rows, and evidence of delays of about 0.2s between rows was apparent in the observed seismic waveforms. (The ripple-firing method minimizes ground vibration and fractures rock more efficiently.) Smith (1989) describes high-frequency seismic signals a few hundred km.

from explosions at a taconite mine. He and Hedlin *et al.* (1989) describe the effects of ripple firing on the spectra of observed seismograms.

Another source of information on how many explosions occur in a limited part of the U. S. was a preliminary study done at the Lamont-Doherty Geological Observatory of the number of blasts detected on the New York State Seismic Network in a single month. It was found that for April, 1986, about 19 explosions were detected per weekday.

The present study of blasting activity in the U. S. is based on three different sources of information: the U. S. Bureau of Mines (USBM); the Mine Safety and Health Administration (MSHA); and Vibra-Tech Engineers, Inc.

The USBM collects data on "apparent consumption" of explosives, i.e. on amounts manufactured. The information is derived from explosives manufacturers and is compiled for a given year by state for different types of explosive.

The MSHA maintains a list of active and inactive surface and underground mines. Although there is no indication of blasting activity we can infer such activity for certain types of operations, and we will compare location counts with this list.

Vibra-Tech Engineers, Inc., are consultants to the mining, quarrying, construction, and explosive-using industries. A major concern of these industries is their environmental impact, such as the effect of ground vibration and air overpressure, due to explosions, on nearby structures. Many mine operators use Vibra-Tech, or other consultants, to monitor the levels of vibration and overpressure in order to document compliance with local regulations limiting the levels of vibration and overpressure. From Vibra-Tech records for 1987, we have acquired data on explosion location, date, approximate time of day, total explosives used in each shot, and maximum pounds per delay period. This database is a detailed description of 20,813 blasts carried out at 532 locations.

Note that, for regulatory purposes, the "maximum pounds per delay period" is *defined* to be the amount of explosives designed to be detonated within an 8 ms interval: the weights of two explosive charges will be counted together if their nominal firing times are within 8 ms.

In sections that follow, we describe in more detail the data from our three different sources (USBM, MSHA, Vibra-Tech). We then describe our methods for extrapolating the Vibra-Tech data to obtain an overview of blasting for the whole U. S., and conclude with some comments on the relevance of these statistics to the nuclear explosion discrimination problem.

DATA ON BLASTING FROM THE U.S. BUREAU OF MINES

An annual USBM publication (see references) reports the total apparent consumption of industrial explosives each year for each state for different types of operation (mining, quarrying), using information supplied by manufacturers of explosives.

Table 2 reproduces the summary figures for five different classes of explosive for the years 1986, 1987, 1988, and 1989.

TABLE 2

Class of Explosive	1986	1987	1988	1989
Permissibles	16,100	15,400	12,600	10,400
Other High Explosives	59,900	65,100	68,500	64,000
Water gels, slurries, emulsions	191,000	218,800	299,200	291,800
ANFO	294,700	286,300	394,300	348,600
Unprocessed AN	1,221,400	1,459,000	1,378,500	1,469,400
Totals	1,783,100	2,044,700	2,153,000	2,184,200

Amounts of industrial explosives sold for use in the U. S., 1986 - 1989 (in metric tons).

In Table 2, permissibles are high explosives (like dynamites) which may be used in underground mines. ANFO is the predominant explosive in use today. It attracted wide attention for the first time in April, 1947, when two Liberty ships carrying ammonium nitrate, a fertilizer, blew up in Galveston County, Texas, with the loss of about 600 lives (Kinney and Graham, 1985). Water gels, slurries, and emulsions are ANFO-like products which have been modified to make them usable in the presence of water. Note from Table 2 that the bulk of the apparent U. S. consumption is unprocessed ammonium nitrate (AN), which is mixed with fuel oil (often on-site at mines) by other manufacturers.

We shall be concentrating on the statistics for 1987, showing a total of about two megatons, which is representative of recent years.

The USBM reports for 1987 that of the two megaton total, 72% was used in the mining of coal; 7.5% in mining for metal ores; 11% in quarrying and non-metal mining; and 7% for construction. Surface mining for coal uses large explosions, where possible, since the purpose is to remove overburden. Most of the coal is used in generation of electricity, an industrial activity that is not greatly affected by short-term (one or two-year) business cycles. Seven states collectively manufactured 55% of the explosive, with Kentucky making more than twice as much as the next state, Pennsylvania, followed in order by Ohio, West Virginia, Wyoming, Georgia, and Alabama. Table 3 shows in order the fifteen states making more than 50,000 tons of explosives in 1987, with breakdown into different types of blasting agent (high explosives are not shown – the totals are relatively small). Also shown is the breakdown into usage in coal mining and metal mining. Note that the USBM figures, by state, are for explosives produced; consumption presumably may be in a different state.

TABLE 3

State	Total explosives	Water gels slurries emulsions	ANFO	Unprocessed AN	Coal mining	Metal mining
KY	382,600	26,800	92,900	250,200	337,200	4,000
PA	167,800	14,100	17,400	131,600	146,800	200
OH	130,500	6,800	20,400	100,900	104,300	400
WV	127,500	3,200	21,200	100,100	119,600	400
WY	118,200	27,300	4,000	85,100	112,400	2,500
GA	96,600	6,000	3,200	86,100	80,900	-
AL	94,400	4,900	3,200	85,000	86,500	100
IN	68,700	15,500	19,200	32,700	61,400	300
AZ	63,500	7,800	1,500	53,200	18,900	42,700
NJ	63,200	1,100	1,500	59,300	59,300	-
VA	62,500	6,500	5,800	44,700	55,300	100
NM	56,800	5,700	500	50,000	31,300	12,200
IL	53,600	8,800	5,000	37,900	41,700	200
MO	52,300	5,100	8,500	33,900	22,300	500
MT	51,400	1,900	700	48,100	36,800	13,500
Other States	507,400	77,300	81,300	260,200	149,300	77,600
Total U.S.	2,044,700	218,800	286,300	1,459,000	1,464,000	154,700

Tons of industrial blasting agents sold for consumption in the U. S. in 1987, and the usage in coal and metal mining, for the 15 states manufacturing more than 50,000 tons of explosives (USBM data).

DATA OBTAINED FROM THE MINE SAFETY AND HEALTH ADMINISTRATION

The MSHA maintains lists of active, temporarily abandoned, and permanently abandoned mines, both surface and underground, in the U. S. Table 4 and Figures 1 - 4 summarize the MSHA information most pertinent to our survey.

Thus Table 4 shows the distribution, by state and by type, of about 4000 active surface mines.

TABLE 4

State	Coal	Metal	Crushed Stone	Cement	Lime	TOTAL
AL	71	0	36	5	5	117
AK	5	4	38	0	0	47
AZ	3	31	15	1	2	52
CA	0	23	68	5	4	100
CO	9	2	7	2	1	21
CT	0	0	3	0	0	3
DE	0	1	0	0	0	1
FL	0	2	115	6	1	124
GA	0	0	68	2	0	70
IA	1	0	0	0	0	1
ID	0	6	3	1	1	11
IL	33	1	46	1	1	82
IN	56	0	41	1	1	99
KS	3	0	48	0	0	51
KY	498	0	57	1	0	556
LA	2	1	11	0	1	15
MA	0	0	11	0	0	11
MD	27	0	20	1	2	50
ME	0	0	0	1	0	1
MI	0	6	9	1	2	18
MN	0	13	5	0	0	18
MO	7	2	91	0	1	101
MS	0	0	2	0	0	2
MT	7	9	4	0	0	20
NC	1	0	85	0	1	87
ND	8	0	0	0	0	8
NE	0	0	2	0	0	2
NH	0	0	4	0	0	4
NJ	0	2	20	0	0	22
NM	6	8	8	0	0	22
NV	0	65	7	2	2	76
NY	0	1	37	3	0	41
OH	159	0	68	0	2	229
OK	17	0	52	0	0	69
OR	0	1	37	2	0	40
PA	539	2	107	6	9	663
RI	0	0	0	0	0	0
SC	0	3	34	0	2	39
SD	0	5	3	1	1	10
TN	42	3	81	1	1	128
TX	12	14	135	3	2	166
UT	2	12	6	1	0	21
VA	153	2	86	1	1	243
VT	0	0	10	0	0	10
WA	2	0	46	4	0	52
WI	0	1	21	0	4	26
WV	396	6	20	0	1	423
WY	25	4	6	0	0	35
TOTAL	2084	230	1573	52	48	3987

MSHA summary of active surface mines.

In Figures 1 - 3 we show the distribution by state of coal mines, metal mines, and quarries for crushed and broken stone. Figure 4 shows total surface mines by state.

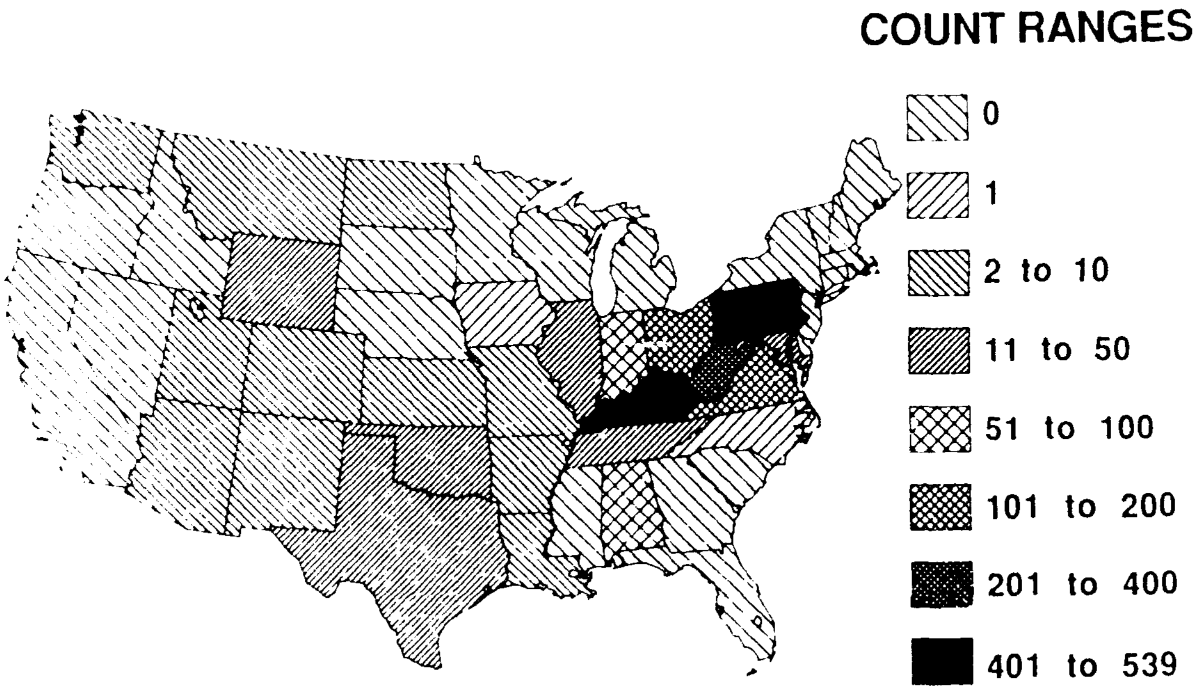

Figure 1. These surface coal mine locations from MSHA have many shots of large size, and constitute both the bulk of explosive use (according to USBM data), and dominate the Vibra-Tech data for large shots.

Note that Wyoming does not have many mines. However, it uses large amounts of explosives, so some mines must have many large shots. The largest shot in our study, just under 3,000,000 lbs. (1,350 metric tons) was from Wyoming.

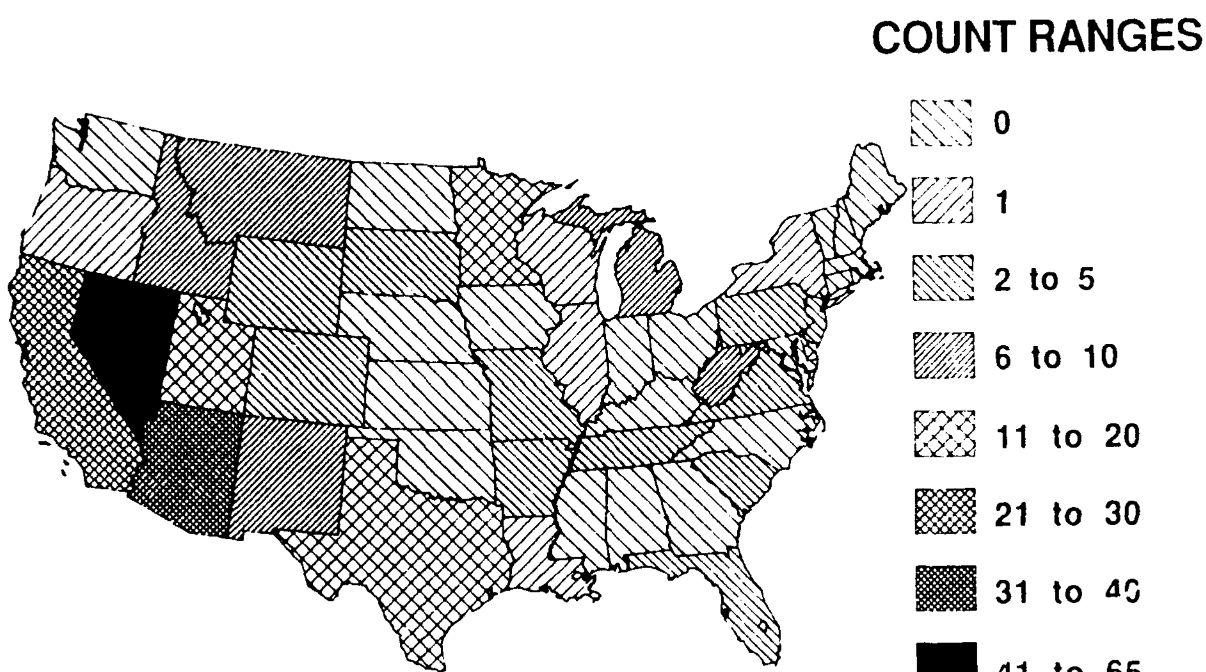

Figure 2. Surface metal mine locations from MSHA. This is the worst- represented type of blasting in the Vibra-Tech database, since these mines tend to be remote and do not monitor. Vibra-Tech does have records from gold mines in California, whose shots are average size, in the range of 10 tons total; and also from iron mines in Michigan (upper peninsular), where the shots are large (some greater than 50 tons total).

Metal mines shoot large shots: the largest mining shot on record (as reported by the Institute of Makers of Explosives) is a 4.1 million pound shot at a copper mine in Arizona in 1983.

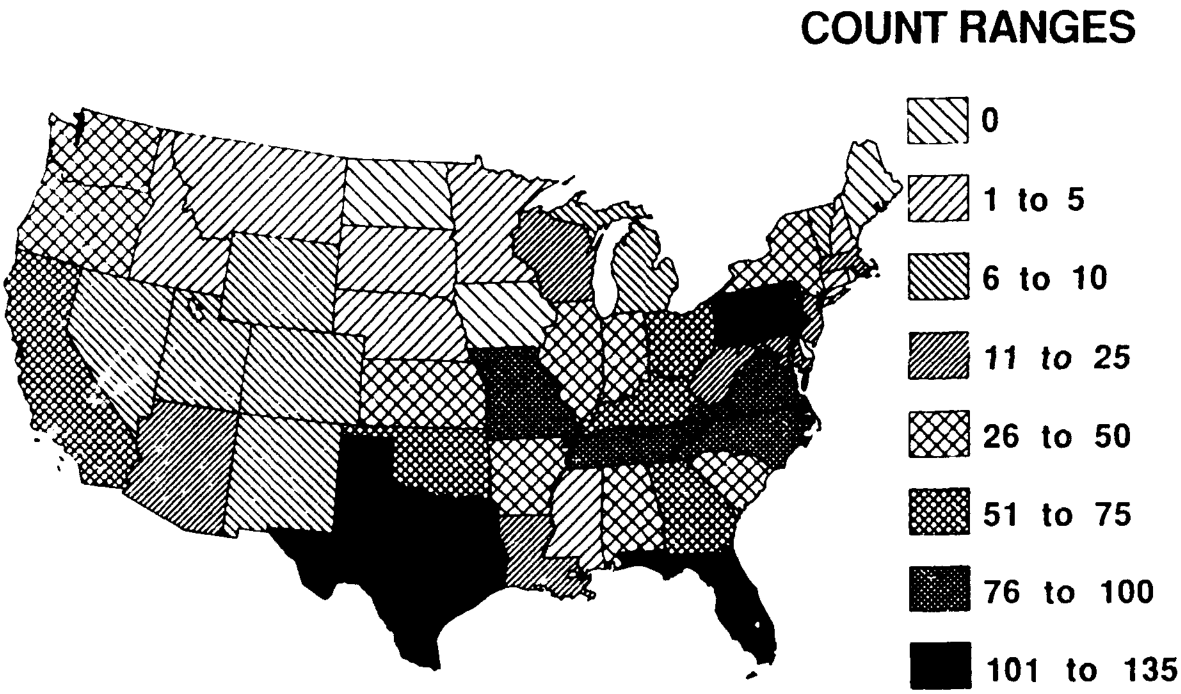

Figure 3. Locations from MSHA of quarries for crushed and broken stone. Such quarries are replaced in much of the West by sand and gravel operations, which do not blast. Note the many quarries in Texas, Florida, North Carolina, and Missouri. These states do not have very high total explosives use, but blast at many locations.

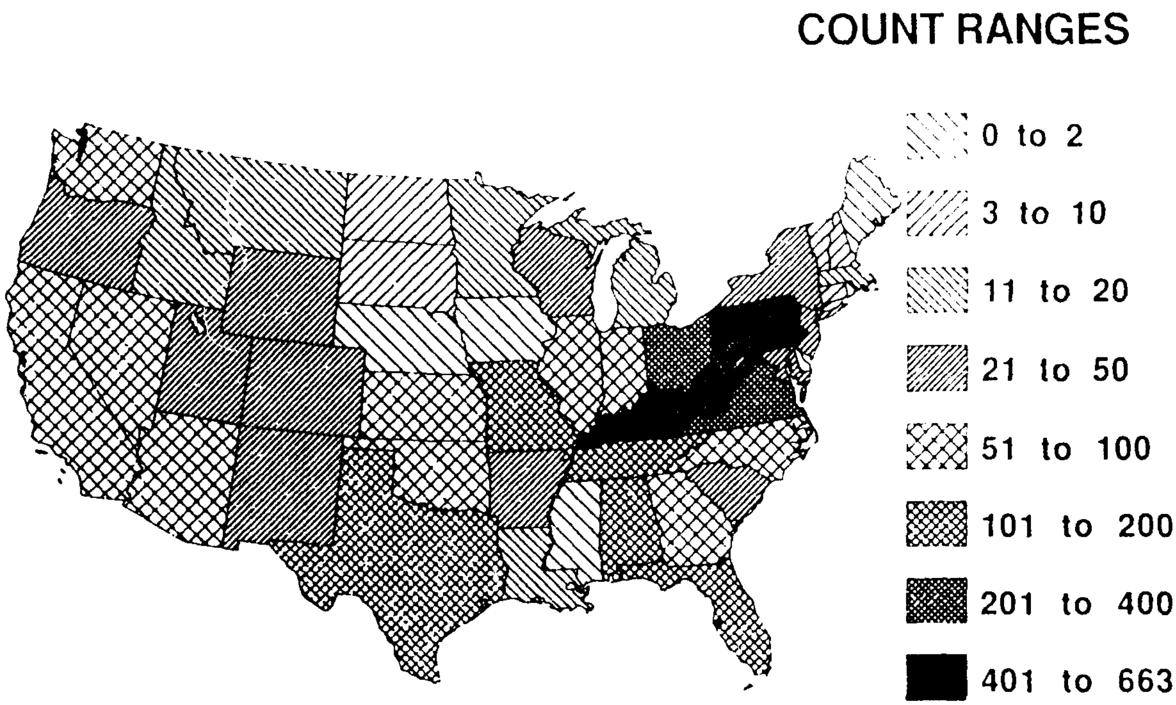

Figure 4. This is a total of coal, metal, crushed and broken stone, lime, and cement surface operations listed by MSHA. There may be blasting in some other mining operations (such as for specialty minerals). There is also blasting for underground mining and construction, but we have specifically excluded these because they tend to be small shots.

The distribution of mines is, in general, consistent with the use of explosives (see Table 3). Variations are principally due to the fact that quarries tend to be smaller in size, and constitute a substantial fraction of the mine count (see Figure 3).

DATA ON BLASTING OBTAINED FROM VIBRA-TECH

As noted above, the records obtained by Vibra-Tech are related to potential claims of damage from blasting to residential and other structures. Quarries must be fairly close to their market (generally within a 30-mile radius) to be competitive; therefore, they often have neighbors, and monitor routinely. In contrast, metal, coal, and specialty mineral mines, which typically shoot the largest shots, are located where the ore or coal is, and may be at a substantial distance from neighbors. Therefore, they sometimes do not monitor their shots. Coal mines generally tend to shoot smaller shots where they are close to residential areas, and then they routinely monitor. Construction operations are very often in congested areas, shoot very small shots, and monitor. There are exceptions to the above, but in general, we would expect to find that Vibra-Tech records are skewed to smaller shots, both in terms of total shot size, and pounds per delay, relative to all mine blasting. Except for a very few of the locations, our data as reported in this study are from mines and quarries.

For 1987, Vibra-Tech had monitoring records from seventeen different offices — four in Pennsylvania and one in each of the following states: Alabama, Colorado, Georgia, Florida, Illinois, Kentucky, Maryland, Missouri, New Jersey, New York, North Carolina, Texas, and West Virginia.

From these seventeen offices engaged in monitoring, information was gathered on shot location (to the nearest tenth of a degree), date and approximate local time, total explosives used, and maximum pounds per 8 ms interval. Detailed Vibra-Tech records for 1987 comprise 294,355,502 total pounds of explosive, detonated in 20,813 shots at 532 locations. This information is summarized first in Table 5 and Figures 5 - 10, where each shot is characterized only in terms of total charge. We describe the distribution of delays later.

TABLE 5

State	# of locations	# of shots	Pounds of explosive	% monitored
AL	7	1,053	71,756,225	35%
AZ	2	5	273,574	0%
CA	2	5	68,250	
CO	6	59	262,975	
CT	4	66	399,735	
FL	4	268	356,904	
GA	33	1,806	26,843,500	13%
IA	15	[illegible]	684,137	
IL	12	491	1,444,567	
IN	10	739	4,218,888	3%
KS	1	41	110,190	
KY	28	2,146	49,739,705	6%
MA	2	12	121,849	
MD	23	1,156	12,583,118	
MI	1	132	17,285,712	
MN	3	464	2,283,217	
MO	10	147	1,125,835	
MT	1	15	62,638	
NC	31	1,199	5,567,877	
NH	1	12	2,698	
NJ	12	641	5,545,928	4%
NY	36	879	7,997,119	
OH	4	101	496,906	0%
PA	202	6,736	61,649,765	17%
SC	11	537	4,994,448	
TN	8	406	1,989,543	
TX	7	197	755,350	
VA	48	1,434	9,528,789	
WI	1	5	14,249	
WV	2	42	1,034,134	0%
WY	5	81	5,157,677	2%
TOTAL	534	20,974	294,355,502	

Total explosive use by state monitored by Vibra-Tech in 1987. The appropriate figure for the number of records with known total explosive is 20,813 rather than 20,974, since no total pounds were listed for a few of the recorded shots; the lower number is used in the text. The last column gives the Vibra-Tech monitored explosive as a percentage of total explosive sold (see Table 3), for the top ten explosive-manufacturing states.

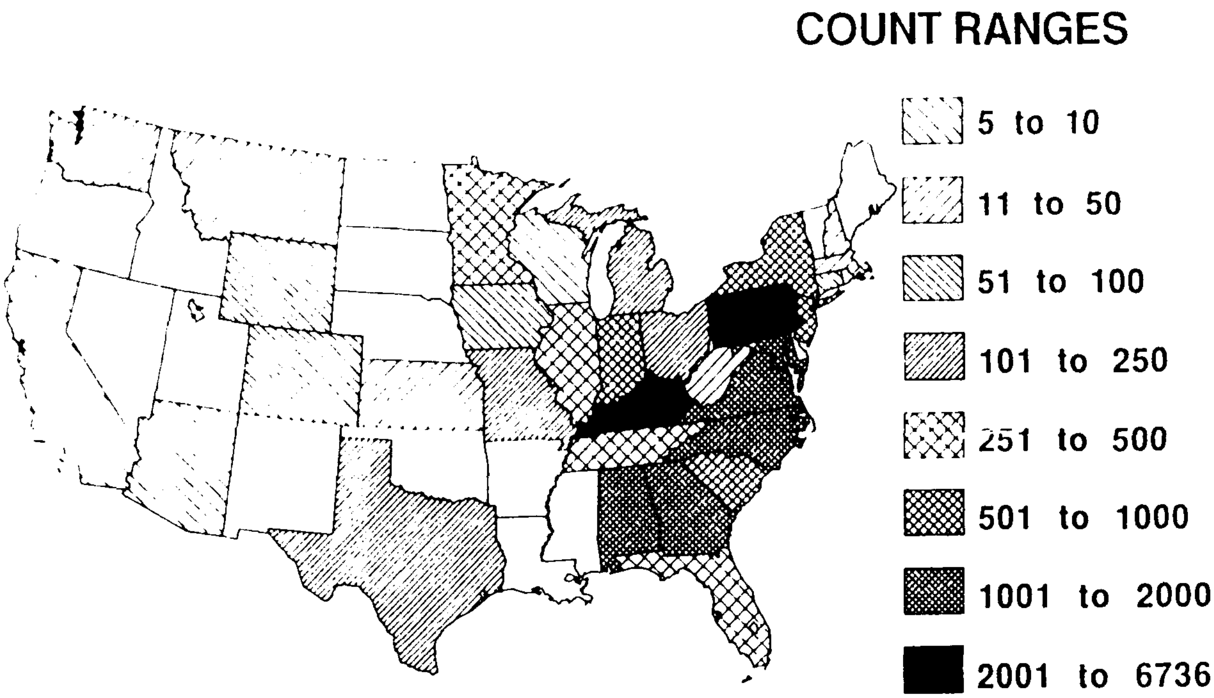

Figure 5. Map of total shots recorded by Vibra-Tech in 1987.

The shot distribution, shown spatially in Figure 5, is skewed to the regions where Vibra-Tech has offices. The distribution of explosive use, shown in Figure 6, is similarly skewed but does compare favorably with USBM data (Table 3) in showing highest levels for Pennsylvania, Kentucky, Alabama, and Georgia.

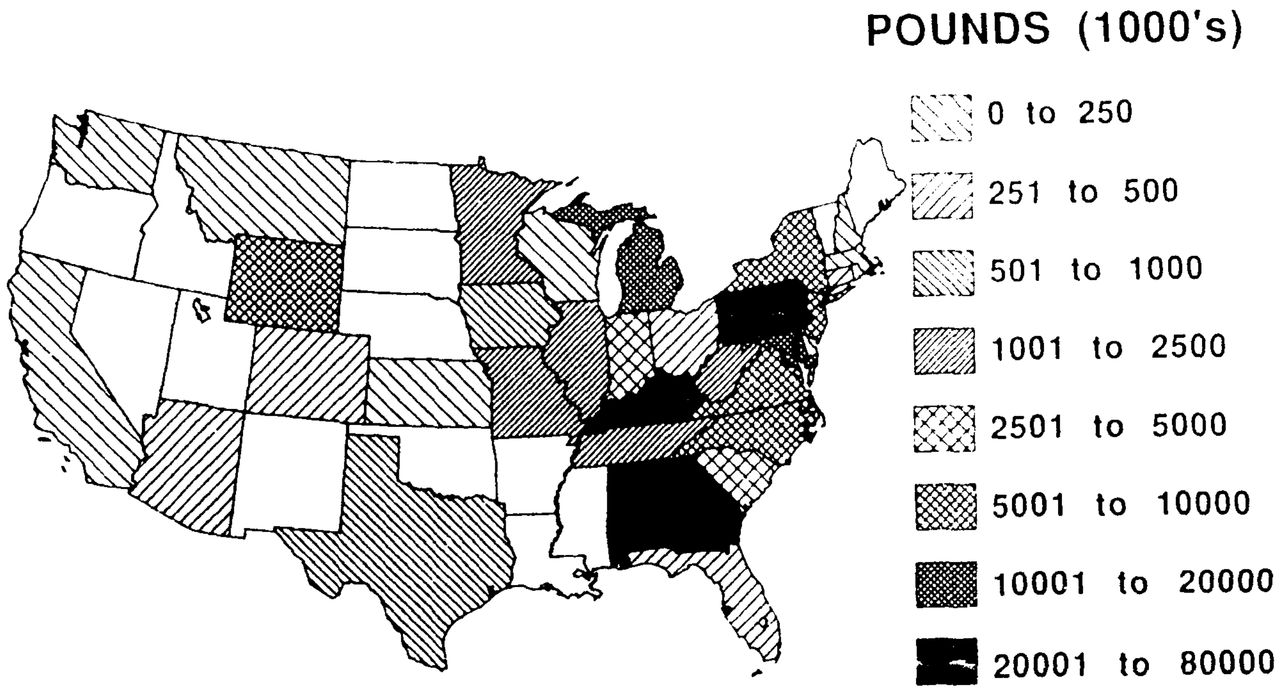

Figure 6. Map of total explosive use, monitored by Vibra-Tech in 1987.

In order to summarize the distribution of sizes of the 20,813 monitored shots, we broke the data into three categories: small, medium, and large shots, where small is less than 10,000 pounds total; medium is from 10,000 to 100,000 pounds; and large is above 100,000 pounds. Figure 7 shows the number of medium shots monitored by Vibra-Tech, by state, for 1987. Shots of this size are used in coal and metal mining and in quarries, and the similarity between Figure 7 and the map of all MSHA surface mine locations (Figure 4) is an indication that Vibra-Tech monitoring data is representative of U. S. blasting for shots in the range 5 to 50 tons.

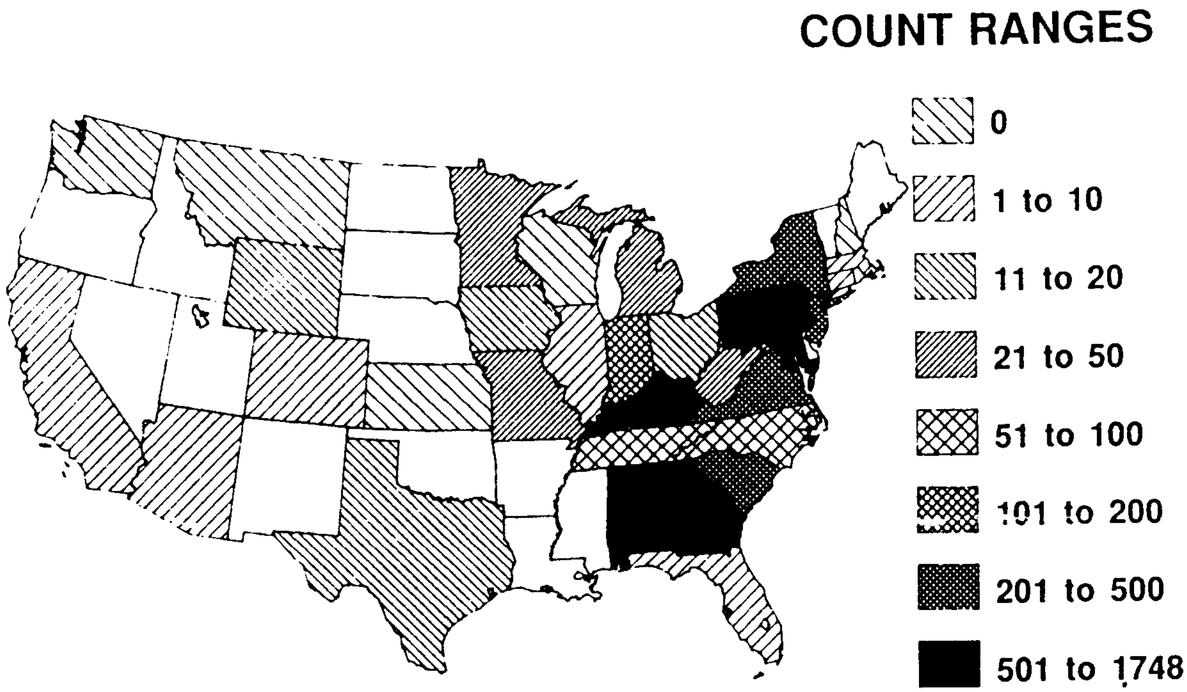

Figure 7. Map showing distribution of Vibra-Tech monitored shots in size range from 10,000 to 100,000 pounds (approximately 5 to 50 tons) in 1987.

Figure 8 shows, by state, the number of large shots, monitored in 1987. Note that distribution is concentrated in the coal mining states. Arizona, while primarily known for copper mines, also has two very large coal mines. The high concentration of large blasts in Michigan is from upper peninsular taconite mines (iron ore).

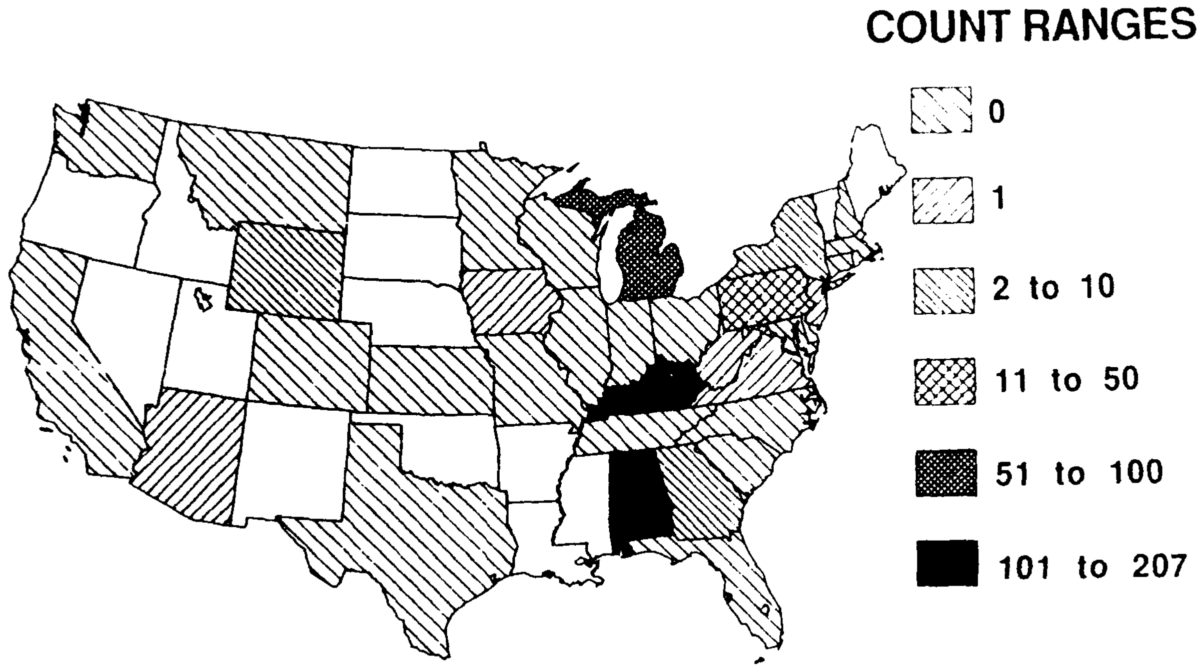

Figure 8. As Figure 7, but for Vibra Tech monitored shots greater than 100,000 pounds.

To show the distribution of shot sizes in more detail (i.e. better than the three categories "small", "medium", and "large"), we show in Figure 9 a histogram for the 20,813 monitored shots. Almost three-quarters of the shots fall in the range of 2,000 to 20,000 pounds total explosive.

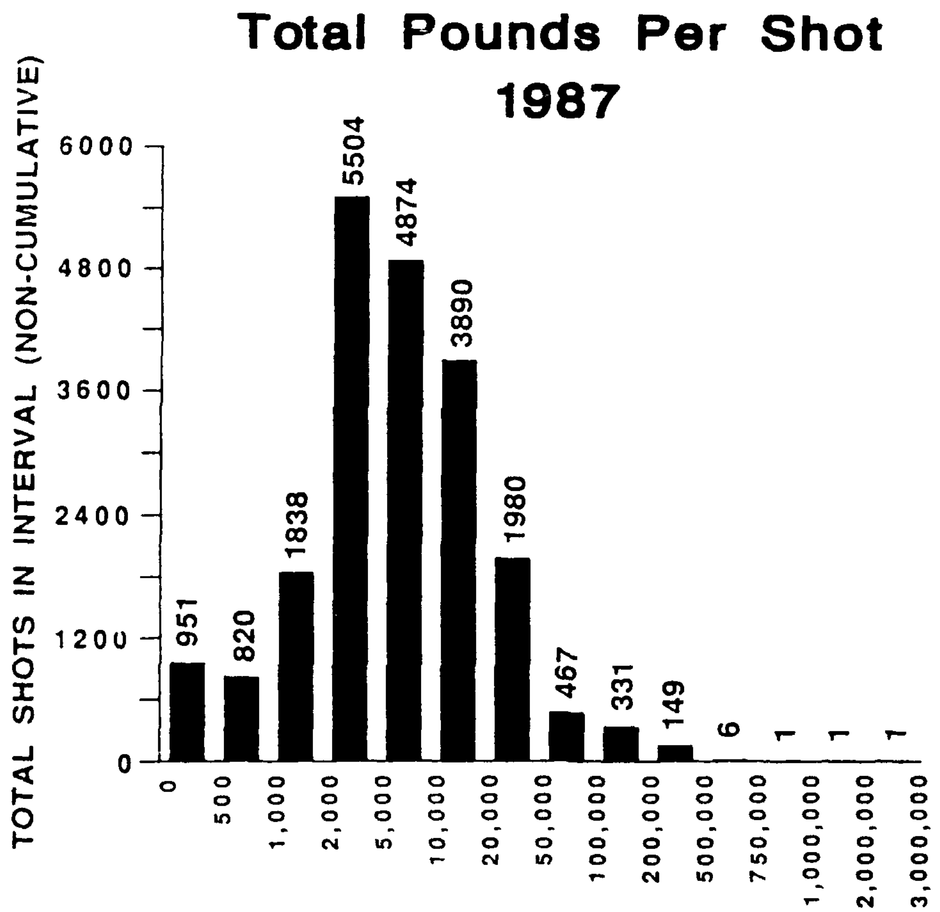

Figure 9. Histogram of Vibra Tech monitored shots in various ranges -- total pounds.

Note that there is a slight peak at the lowest range (0 to 500 pounds). If more construction shots were included in the data, this peak would be further emphasized. There are almost 500 shots greater than 100,000 pounds. The largest shot monitored by Vibra-Tech in 1987 was 2,968,998 pounds (1,350 tons) in a Wyoming coal mine on March 20.

Another way to describe the distribution of shot sizes, is in terms more closely related to the usual method for describing the size distribution of earthquakes, in which the cumulative count $N = N(m)$ is defined to be the number of earthquakes occurring (in some time interval) with magnitude greater than m. Working with the logarithm of shot size, we show in Figure 10 the cumulative count of Vibra-Tech monitored shots in 1987.

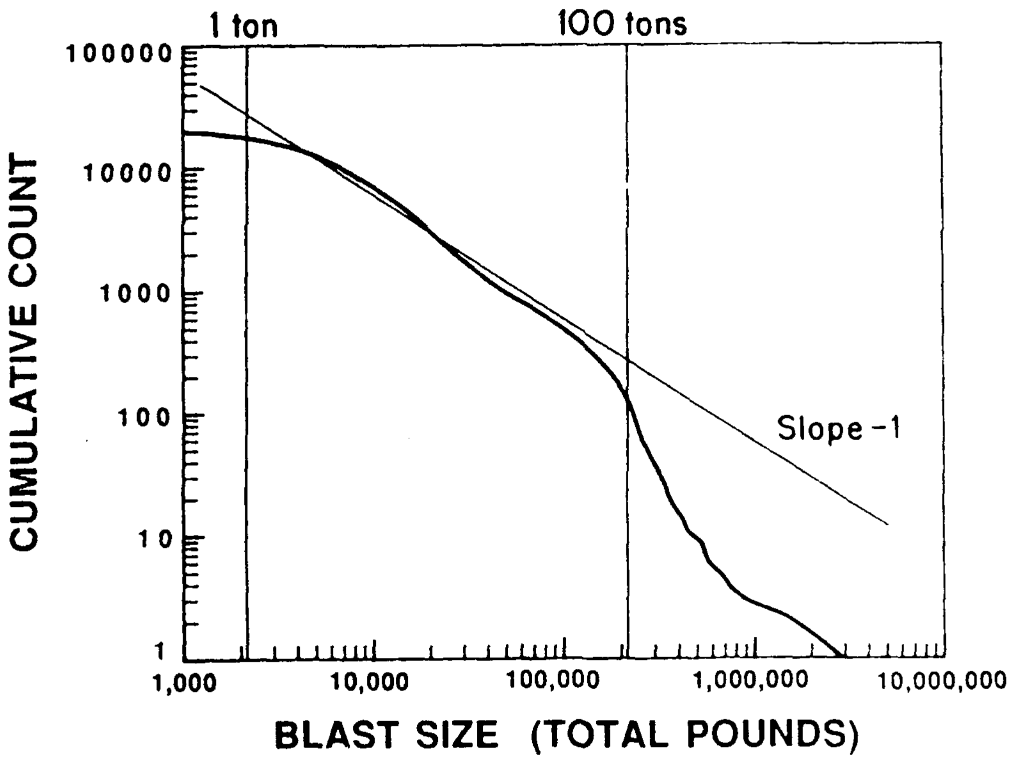

Figure 10. Cumulative count vs. blast size, for Vibra-Tech monitored shots.

It is interesting that Figure 10 indicates a slope of about -1 from 1 ton to 100 tons. This is remarkably similar to the result

$$N \propto 10^{-b\, m_b}.$$

with b-value near unity, as found for the distribution of body wave magnitudes for earthquakes. The fact that the "b- value" in Figure 10 is greater than unity for shots above 100 tons, is perhaps in part because Vibra-Tech undersamples this size range.

Finally, in this section on monitored explosions, we comment briefly on the distribution of delays. We have information on pounds per delay for 20,759 shots, and a histogram is shown in Figure 11. The distribution is unimodal, with a sharp peak in the 200- to 500-pound range. This peak is a consequence of physical limitations on borehole diameter and depth. Apart from a couple of shots with delays in the range 30 – 100 tons, the remaining shots (including 487 shots with total charge greater than 50 tons) have delays less than 10 tons each. We found that most shots had the pounds per delay approximately 2 to 5% of the total explosive in the shot.

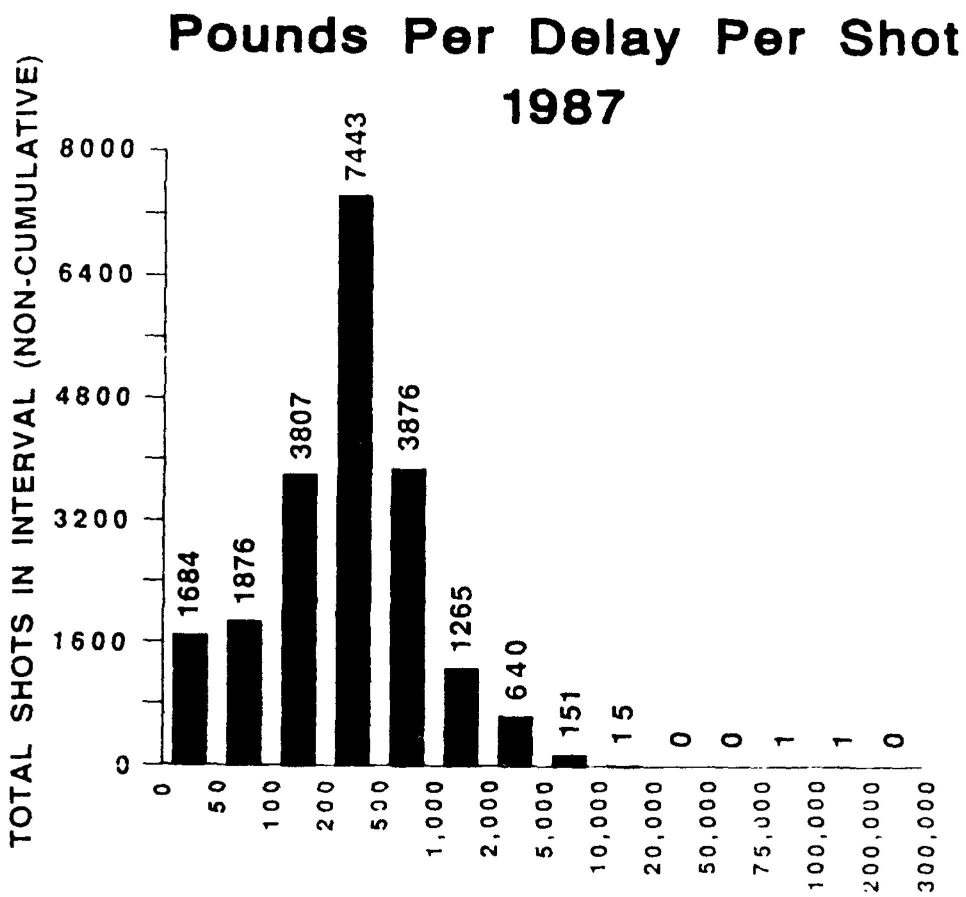

Figure 11. Histogram of pounds per delay, for monitored shots.

The only shots which used no delay were all small: ripple-firing was the universal practice for medium and large shots. Further information on the distribution of delays is given in the Appendix.

COMPARISON OF MONITORED SHOTS, WITH USBM AND MSHA DATA

Since we are interested in estimating the number of large blasts annually in the U. S., we have sought to extrapolate the Vibra-Tech data on monitored shots using information from USBM and MSHA as constraints. In this section we first state our initial expectations – our guesses – before we had any data. We then show how these initial estimates can be refined.

We initially estimated that Vibra-Tech has about 40% of the market share for blast monitoring, and that approximately half of the surface mining operations use a vibration consultant. On this basis, Vibra-Tech would have records for about 20% of the operations in the U. S. However, this is the percentage of *locations*, rather than explosive use. Since records of explosive use will be skewed towards smaller shots, our initial expectation was that an even smaller percentage of the total explosive use would be covered, perhaps about 10%. Operations which shoot large shots will generally shoot fewer shots, and we expected that our monitoring data would cover about 15% of the shots – that is, between the percentages for locations (20%) and for total explosive use (10%).

We can refine these initial estimates, and reach conclusions on the numbers of large shots, by taking the following three steps:

1) It appears that Vibra-Tech has records in 1987 for fewer than 20% of the blasting operations in the U. S., since the MSHA lists 3987 active surface mines (see Table 4) and Vibra-Tech monitored 532 locations. This is 13% of the MSHA total. Similarly, Vibra-Tech monitored somewhat less than 10% of the total explosive used since about 2 megatons are reported by USBM (Table 3) and Vibra-Tech monitored about 134 kilotons (294 million pounds; see Table 5). This is 6.5% of the USBM total.

2) The percentage for the number of shots monitored by Vibra-Tech, initially estimated as 15%, must also be scaled back somewhat. We would still expect this percentage to lie between the percentages for locations (13%) and total explosive use (6.5%), hence we estimate that Vibra-Tech monitored about 10% of the shots.

3) We recognize that large shots (> 100,000 pounds, i.e. about 50 tons) are under-represented in the Vibra-Tech database, perhaps by a factor of two. (We show this is a conservative estimate, in discussion of Table 6, below.)

From these three steps and their associated assumptions, we therefore estimate that Vibra-Tech monitored about 5% of the large U. S. shots in 1987. Our conclusions are summarized in Table 6.

TABLE 6

Shot size	Vibra-Tech Count	Estimated % of total	Estimated Total Count
Small (< 10,000 lb)	13,987	?	
Medium	6,337	10 %	65,000
Large (> 100,000 lb)	489	5%	10,000

Summary by shot size of Vibra-Tech monitored explosions, and estimated annual U. S. total counts. The latter estimates are somewhat conservative, i.e. best estimates would be somewhat lower.

Another way to improve our initial estimates is to explore the consequences of the rule

$$N \propto 10^{-b \log W}$$

for the cumulative count (see Figure 10). This rule is equivalent to a power law,

$$N = aW^{-b},$$

and we can relate it to the total amount of explosive whose use was monitored by Vibra-Tech.

The total (294 million pounds, from Table 5) is about 135 kilotons, and it is interesting to determine whether this amount is principally built up from the fewer large explosions (> 100 tons), or from the medium range for which we have reason to believe the Vibra-Tech database is representative of U. S. blasting, or from the large number of small explosions (< 1 ton). The problem is similar to that of identifying the principal contribution to the total moment for a set of earthquakes associated with a power law distribution of fault sizes (Scholz and Cowie, 1990).

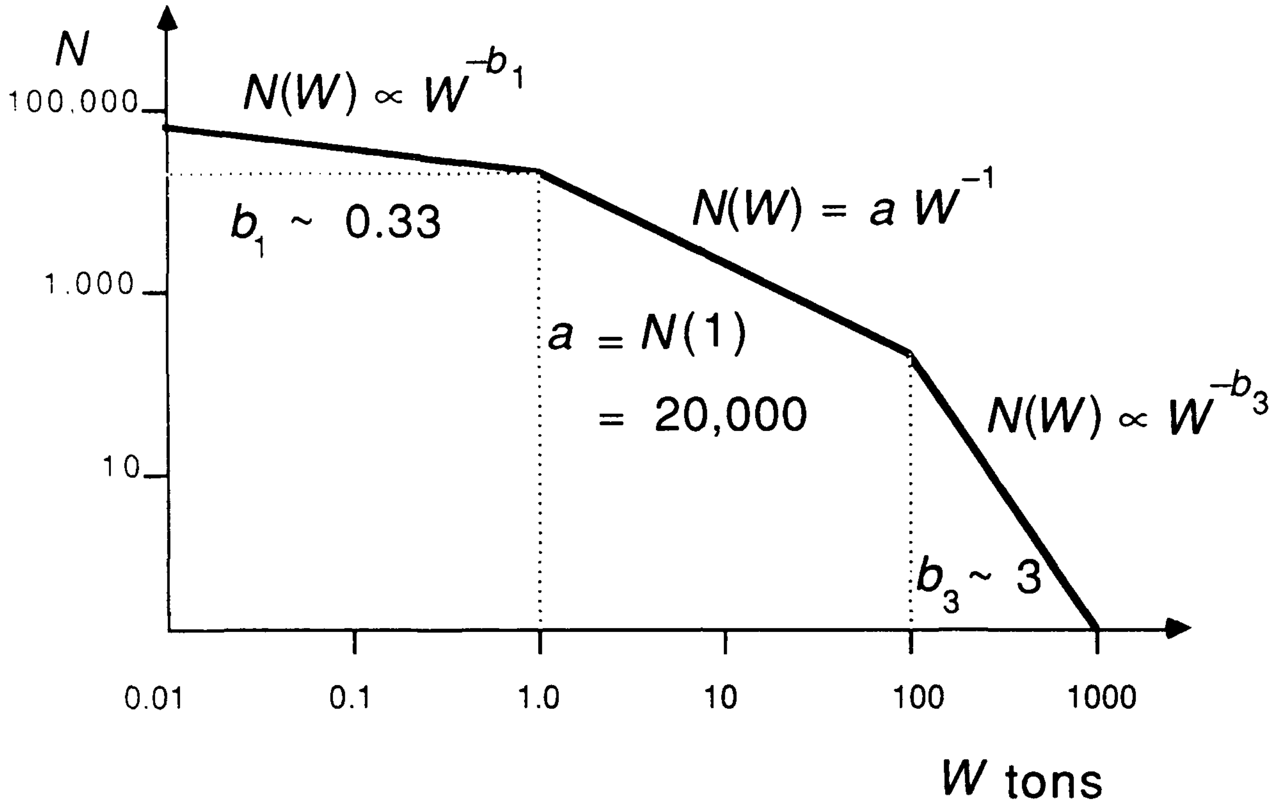

Figure 12. A fit, by three line segments, to the Vibra-Tech data on cumulative count shown in Figure 10. This is a log-log plot, with a power law $N = a_i W^{-b_i}$ for each segment ($i = 1, 2, 3$).

The total amount of explosive accumulated for all shots between sizes W_{min} and W_{max} is related to N via an integral:

$$\text{Total explosive} = -\int_{W_{min}}^{W_{max}} W \,.\, \frac{dN}{dW} \,.\, dW \tag{1}$$

For the cumulative count shown in Figure 12, we can let $W_{min} \to 0$ and $W_{max} \to \infty$ and still get a convergent integral, finding:

$$\text{Total explosive} = N(1)\left(\frac{b_1}{1 - b_1} + 2\log_e 10 + \frac{b_3}{b_3 - 1}\right) \tag{2}$$

The three terms here correspond respectively to the totals contributed from explosions smaller than 1 ton, from explosions between 1 and 100 tons, and from explosions larger than 100 tons. The critical b-value of unity (assumed here between 1 and 100 tons) is precisely that which ensures a constant contribution to the total, per decade in W. Choosing $b_1 = 0.33$, $b_3 = 3$, and $N(1) = 20{,}000$, which seem appropriate from Figure 10, equation (2) does give an accurate result (132 kilotons) for the known total (135 kilotons). The three separate terms are in the ratio 0.5: 4.6: 1.5, and the dominant contribution to the total explosive does come from the middle range (1 to 100 tons).

We are now in a position to discuss quantitatively the cumulative count for all U. S. explosions, making extrapolations from the Vibra-Tech database and using the known value of 2.04 megatons for total explosive use (see Table 1).

If the U. S. cumulative count is the same shape as that for the Vibra-Tech monitored data, then the scaling factor is constant across all W and is just the ratio of the two totals: 2.04 megatons/135 kilotons = 15. It would follow that the two percentages in Table 6 both become 6.5% and there are about 7,500 explosions per year above 50 tons in the U. S., and about 25 above 500 tons (b-value is 3 above 100 tons).

If the U. S. cumulative count shows a higher proportion of large explosions than does the Vibra-Tech data, then we can take an extreme example of such a distribution by assuming that for the decade from 100 to 1,000 tons the b-value is also unity. Neglecting the contribution of small explosions we would find the a-value in the power law $N_{U.S.} = aW^{-1}$ from the integral (equation 1) for total explosive with $W_{min} = 1$ and $W_{max} = 1{,}000$. It then would follow that there are about 6,000 explosions per year above 50 tons in the U. S., and about 600 per year above 500 tons. The big difference from the previous estimate (concerning numbers of very large chemical explosions) is due to continuation of a b-value of unity, rather than $b = 3$, for $W > 100$ tons. However, the difference in numbers of explosions greater than 50 tons is not substantial, and we can have confidence in Table 6 as a summary of conservative estimates.

CONCLUSIONS OF BLASTING SURVEY AND DISCUSSION

The monitoring data gathered in 1987 by Vibra-Tech were compared with explosive-use totals and geographical distribution from the U. S. Bureau of Mines, and to the distribution of mines listed by the Mine Safety and Health Administration. These comparisons indicate that in many respects the monitoring data, which include information on shot sizes, are representative of blasting practices in the U. S.

Shots were divided into three categories of small (<10,000 pounds, about 5 tons), medium (between 10,000 and 100,000 pounds), and large (> 100,000 pounds, about 50 tons). We estimate that total shots in the U. S. for 1987 for the medium-shot category are about 10 times more than monitored by Vibra-Tech, and the total for the large-shot category are about 20 times greater. The small-shot category includes underground and construction blasting, and we have not estimated total U. S. shots in this category. These conclusions are summarized in Table 6.

The number of large shots (greater than about 50 tons) corresponds to approximately 30 per day. From information on blasting agents supplied to a limited number of mines known to carry out shots routinely in the range 100 - 500 tons (see Table 1), we can add that the estimated count of explosions greater than 50 tons would be expected to include at least one per day greater than 200 tons.

If we take the typical shot in the large category as 100 tons, then Table 6 indicates about one megaton a year is used in large chemical explosions in the U. S. If the typical medium-sized shot is 20 tons, then about 1.3 megatons are used annually in this category. When added to the annual total explosive for small shots, it is therefore clear that Table 6, with all its uncertainties, errs on the side of over-estimation – because it implies an overall total explosive use that exceeds the two megatons reported by USBM (Table 3).

The main point, however, from the perspective of those concerned with nuclear explosion monitoring and the question of discriminating between chemical and nuclear explosions, is that a large industrialized country can be expected to carry out large numbers of chemical explosions. If the concern is with identifying all nuclear explosions down to about five kilotons, the intersection with industrial chemical explosions appears manageable if there is a will to take a problem-solving approach to the limited number of evasion scenarios, such as decoupling (U. S. Congress, 1988).

If the concern is with monitoring down to one kiloton, i.e. at yield levels low enough that full decoupling becomes technically more feasible (with decoupling factors around 70 at frequencies below the corner frequency), then monitoring would require a threshold of detection low enough that many thousands of chemical explosions would be routinely recorded. In this situation, the key to robust methods of discrimination will be an understanding of the signals of ripple-fired explosions, as opposed to single-shot explosions. Amplitudes of regional seismic waves are much reduced by ripple-firing.

Our goal in this paper was to get estimates, where none were available, of the numbers of chemical explosions in the United States and to characterize their size distribution. Further work is needed to characterize the distribution of U. S. explosions greater than 50 tons in size. Work is also needed to obtain chemical explosion statistics for other nuclear weapon states, and for countries of concern under the current non-proliferation regime.

ACKNOWLEDGMENTS

We thank Frederick Smith of the Institute of Makers of Explosives and Anne Coughlin of MSHA for technical advice; and Klaus Jacob and Susan Hough for comments on a draft manuscript. This project was supported by the Defense Advanced Research Projects Agency and monitored by the Geophysics Laboratory (later Phillips Laboratory) under Contract No. F19628-88-K-0041.

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APPENDIX

We here give additional detail on chemical explosions monitored by Vibra-Tech Engineers, Inc. in 1987. In particular, we give further information on the size of delays in ripple-fired explosions.

Vibra-Tech collects and maintains records for their clients on blasts on forms like Figure A1. Note that both blast information and seismograph data are recorded on this one form.

VIBRA-TECH ENGINEERS BLAST AND SEISMOGRAPHIC REPORT

BLAST DATA

Client ____________________

Job Location ____________________

Date __________ Blast No. __________ Time __________

Exact Blast Location ____________________

No. of Holes ______ Diameter ______ in. Avg. Depth ______ ft. Subgrade ______ ft.

Spacing ______ ft. Burden ______ ft. Avg. Stemming ______ ft.

Make & Type of Explosives: Delay Make __________

______ ______ ______ lbs. Delay Type & Nos. __________

______ ______ lbs. Min. delay period __________ ms.

______ ______ lbs. Max. lbs./delay period __________ lbs.

______ ______ lbs. Blaster __________

______ ______ lbs. Weather __________

Total Explosives ______ lbs. Wind Direction & Speed __________

DETAILED BLAST INFORMATION

Detail or Diagram Blast Layout: Number of rows; Number of holes in each row; Number of decks per hole; amount of stemming between powder columns; nominal delay time between decks, holes and rows. (Use reverse side if necessary.)

SEISMOGRAPH DATA

Seismograph No. __________ Range/Gain Setting ______ ips | Everlert Only Trigger Level ______ ips

Date of last: Shake Table Calibration __________ Microphone Calibration __________

Air channel low frequency limit __________ Hertz

Exact Seismograph Location ____________________

____

Seismograph Distance & Direction from Blast ____________________

Meters { Peak Overpressure ______ dB Scaled Distance __________

Meters { Peak Particle Velocity ______ ips Operator __________

Remarks: ____________________

Vibration Analysis by: __________ Date: __________

VTE 10?

Vibra-Tech Engineers, Inc.

Figure A1. Typical blast and seismographic report form.

For the study in the accompanying paper, Vibra-Tech transcribed from all these forms for 1987 the following items: job location (to nearest tenth of a degree); date; approximate local time; total explosives; and maximum pounds per 8 ms delay interval.

The data were entered on floppy disk, with one location per file. The first record in each file gives latitude, longitude, city, state, and time zone. The subsequent records in each file give information for each shot in 1987: month; day; hour; minute; pounds per delay; and total pounds in the shot. The records comprise the detailed information behind Table 5 and Figures 5 - 11 of the accompanying paper. The records are also the basis for Tables A1 – A4 and Figures A2 – A5 of this Appendix.

Thus, total shot size as broken down by state is given in Table A1 for shots less than or equal to 50,000 pounds (about 23 metric tons), and Table A2 for shots greater than 50,000 pounds.

TABLE A1

Count of Shots by Total Explosives Use							
State Name	**500**	**1000**	**2000**	**5000**	**10000**	**20000**	**50000**
AL	6	7	16	45	66	163	322
AZ	0	0	0	0	3	0	1
CA	0	0	0	1	0	0	3
CO	0	2	6	39	7	4	1
CT	7	0	0	11	46	2	0
FL	10	62	55	43	7	4	0
GA	55	25	38	151	325	726	474
IA	5	4	2	24	23	11	5
IL	8	6	148	288	37	4	0
IN	7	69	119	211	216	96	21
KS	11	1	3	20	6	0	0
KY	242	160	218	324	334	372	220
MA	0	0	0	1	8	2	1
MD	5	28	85	192	312	397	130
MI	0	0	0	2	4	1	13
MN	1	16	59	220	135	31	2
MO	7	38	33	10	18	17	24
MT	0	0	1	9	5	0	0
NC	8	17	94	685	322	64	0
NH	12	0	0	0	0	0	0
NJ	26	20	39	110	139	133	79
NY	40	16	102	217	270	155	57
OH	1	5	11	52	19	12	1
PA	304	182	477	2148	1832	1132	538
SC	3	0	10	132	173	194	23
TN	108	11	38	73	112	56	6
TX	49	88	6	16	19	10	4
VA	24	37	229	439	396	264	36
WA	0	0	0	0	0	0	0
WI	0	0	2	3	0	0	0
WV	4	0	3	2	6	11	12
WY	2	14	26	6	6	18	2

Distribution of Shots by Total Pounds (≤ 50,000)

TABLE A2

Count of Shots by Total Explosives Use							
State Name	100000	200000	500000	750000	1000000	2000000	3000000
AL	218	138	63	4	1	1	0
AZ	0	1	0	0	0	0	0
CA	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0
CT	0	0	0	0	0	0	0
FL	0	0	0	0	0	0	0
GA	7	2	0	0	0	0	0
IA	0	1	0	0	0	0	0
IL	0	0	0	0	0	0	0
IN	0	0	0	0	0	0	0
KS	0	0	0	0	0	0	0
KY	110	106	44	0	0	0	0
MA	0	0	0	0	0	0	0
MD	6	0	0	0	0	0	0
MI	21	65	25	0	0	0	0
MN	0	0	0	0	0	0	0
MO	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0
NC	0	0	0	0	0	0	0
NH	0	0	0	0	0	0	0
NJ	0	0	1	0	0	0	0
NY	9	1	0	1	0	0	0
OH	0	0	0	0	0	0	0
PA	78	13	5	0	0	0	0
SC	0	0	0	0	0	0	0
TN	0	0	0	0	0	0	0
TX	3	0	0	0	0	0	0
VA	2	1	0	0	0	0	0
WA	0	0	0	0	0	0	0
WI	0	0	0	0	0	0	0
WV	3	0	1	0	0	0	0
WY	0	0	3	1	0	0	1

Distribution of Shots by Total Pounds (> 50,000)

Figures A2 - A5, and Tables A3 - A4, give information on the distribution of delays. Thus, Figure A2 shows the number of shots with pounds per delay calculated as a percentage of the total pounds.

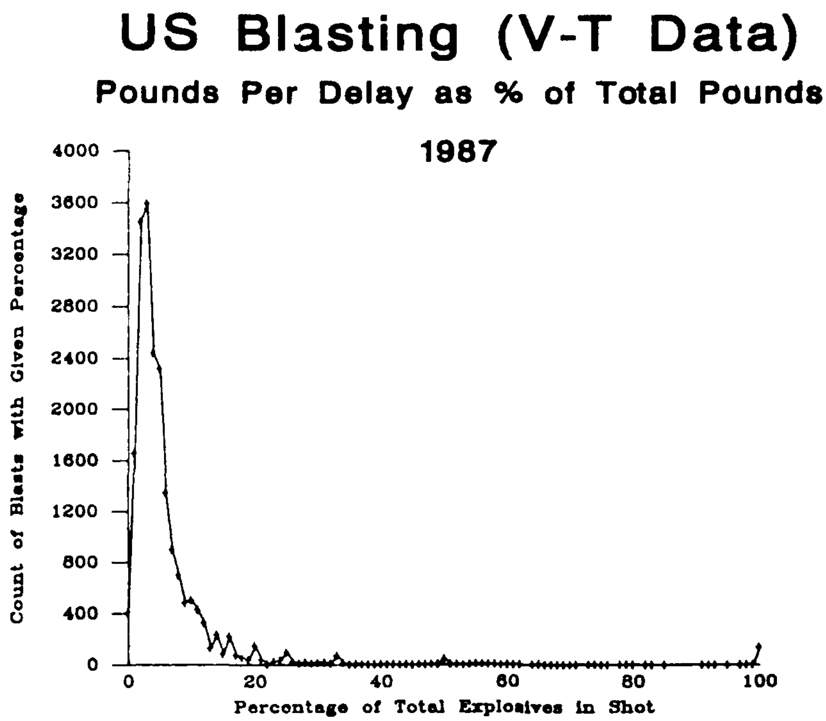

Figure A2. Count of shots versus pounds per delay as a percentage of total pounds.

Most shots had the pounds per delay approximately 2 to 5 percent of the total explosive in the shot. There were 140 shots in which there was no apparent delay. They show at the 100% value in Figure A2. There are also quite a few shots which had greater than the 2 to 5 percent range. The shots with no apparent delay were specially checked. Approximately half of these shots are from one location in a specific time period where the data was improperly recorded, since the other shots at this location have the normal ratio of around 3% of pounds per delay to total pounds. The other shots are all small (< 100 pounds). Some of these are "pop shots", where a small amount of rock must be broken up, typically oversized boulders (which will not fit in the crusher) in quarries. Construction shots may also contribute to this category, since they are primarily small shots.

The geographical distribution of delays of different size is given in Table A3 for pounds per delay less than or equal to 5,000 pounds (about 2.3 tons), and in Table A4 for pounds per delay greater than 5,000 pounds.

TABLE A3

Count of Shots by Pounds Per Delay							
State Name	**50**	**100**	**200**	**500**	**1000**	**2000**	**5000**
AL	33	21	82	220	196	220	200
AZ	0	0	0	0	0	1	3
CA	0	0	2	0	3	0	0
CO	3	3	14	34	5	0	0
CT	7	0	6	42	10	1	0
FL	95	2	27	51	4	2	0
GA	107	60	157	574	822	57	11
IA	4	16	36	19	0	1	1
IL	72	125	49	227	15	0	2
IN	41	246	13	197	242	0	0
KS	2	8	4	27	0	0	0
KY	359	290	307	342	261	344	207
MA	0	0	4	3	5	0	0
MD	14	15	111	457	448	98	7
MI	0	0	0	2	6	32	74
MN	27	46	286	97	6	1	1
MO	49	19	11	18	16	34	0
MT	0	2	10	3	0	0	0
NC	26	229	505	368	37	3	1
NH	12	0	0	0	0	0	0
NJ	34	51	78	162	96	99	24
NY	54	78	121	296	198	54	14
OH	13	15	25	30	9	0	1
PA	395	462	1400	3120	954	267	84
SC	4	0	160	244	123	0	1
TN	94	23	50	218	14	0	7
TX	137	3	7	31	13	5	0
VA	90	150	271	509	377	27	1
WA	0	0	0	0	0	0	0
WI	0	1	1	3	0	0	0
WV	3	1	4	15	9	10	0
WY	0	0	3	71	0	0	0

Distribution of Shots by Pounds per Delay (≤ 5,000)

TABLE A4

Count of Shots by Pounds Per Delay							
State Name	**10000**	**20000**	**50000**	**75000**	**100000**	**200000**	**300000**
AL	65	13	0	0	0	0	0
AZ	1	0	0	0	0	0	0
CA	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0
CT	0	0	0	0	0	0	0
FL	0	0	0	0	0	0	0
GA	2	0	0	0	0	0	0
IA	1	0	0	0	0	0	0
IL	0	0	0	0	0	0	0
IN	0	0	0	0	0	0	0
KS	0	0	0	0	0	0	0
KY	27	0	0	0	0	0	0
MA	0	0	0	0	0	0	0
MD	2	0	0	0	0	0	0
MI	18	0	0	0	0	0	0
MN	0	0	0	0	0	0	0
MO	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0
NC	0	0	0	0	0	0	0
NH	0	0	0	0	0	0	0
NJ	0	0	0	0	0	0	0
NY	0	0	0	0	0	0	0
OH	0	0	0	0	0	0	0
PA	19	0	0	0	0	0	0
SC	0	0	0	0	0	0	0
TN	0	0	0	0	0	0	0
TX	0	0	0	0	0	0	0
VA	0	0	0	0	0	0	0
WA	0	0	0	0	0	0	0
WI	0	0	0	0	0	0	0
WV	0	0	0	0	0	0	0
WY	1	2	0	0	1	1	0

Distribution of Shots by Pounds per Delay (> 5,000)

Finally, we give a sequence of three maps showing the distribution by state of shots with pounds per delay ≤ 500 (Figure A3); pounds per delay greater than 500 and less than or equal to 2,000 (Figure A4); and pounds per delay greater than 2,000 (Figure A5).

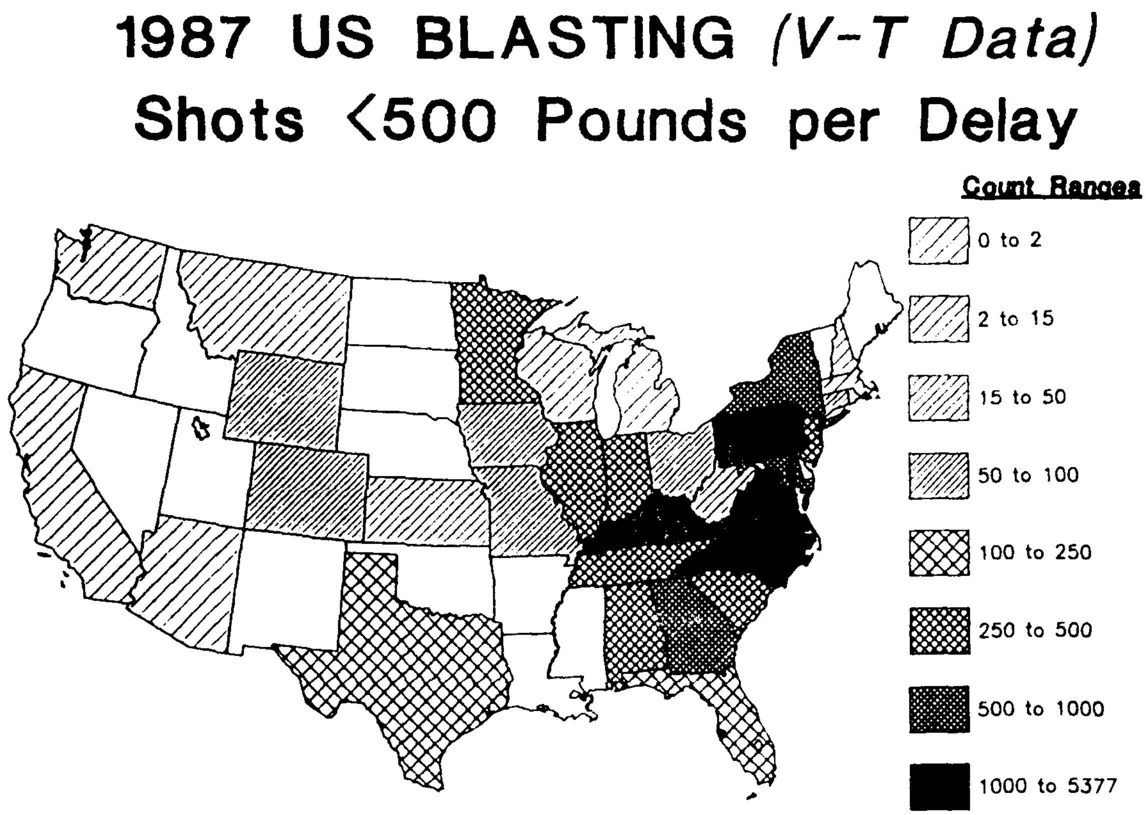

Figure A3. Map showing distribution of shots with pounds per delay ≤ 500. These shots are characteristic of quarry and small coal mine operations.

1987 US BLASTING *(V-T Data)*
Shots 500-2000 Pounds per Delay

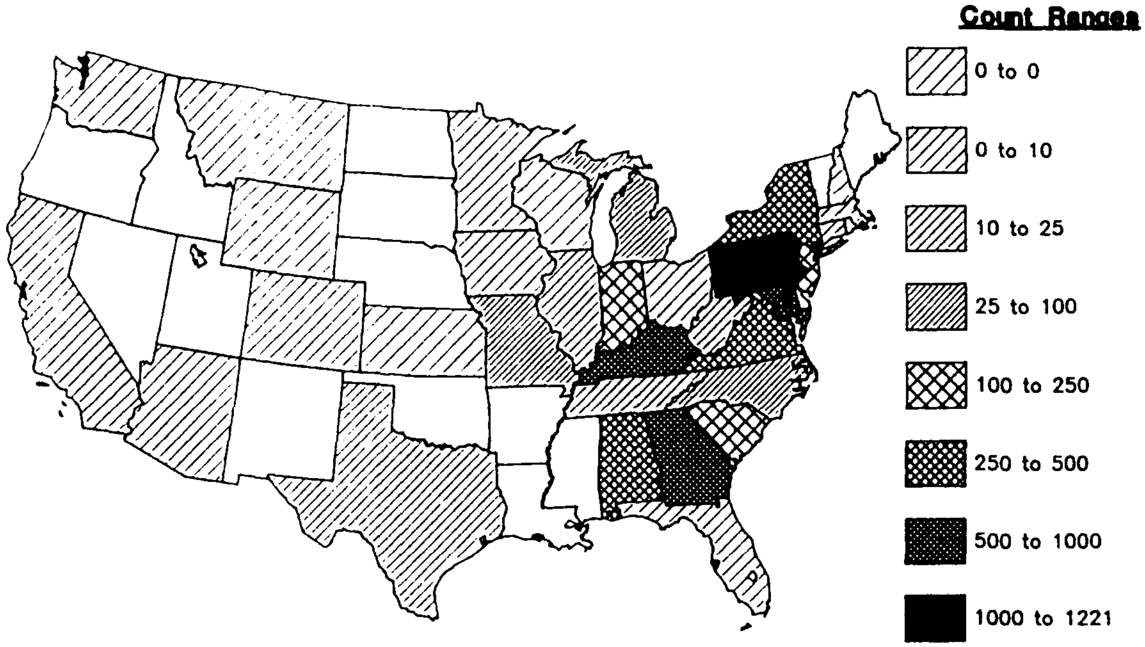

Figure A4. Map showing distribution of shots with pounds per delay > 500 and ≤ 2,000. This is the typical shot in the Vibra-Tech data base, and probably typical too of overall U. S. blasting practice.

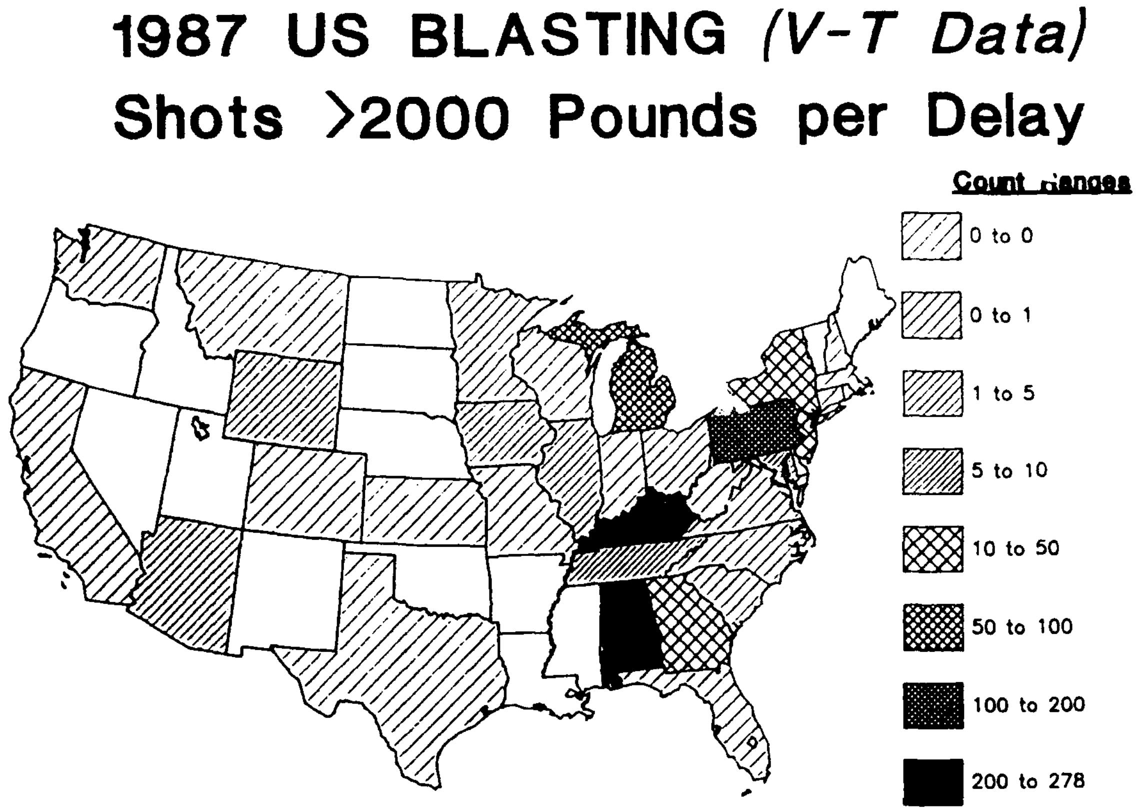

Figure A5. Map showing distribution of shots with pounds per delay > 2,000. These, like the large total pound shots, are from large coal mines and metal mines.

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